



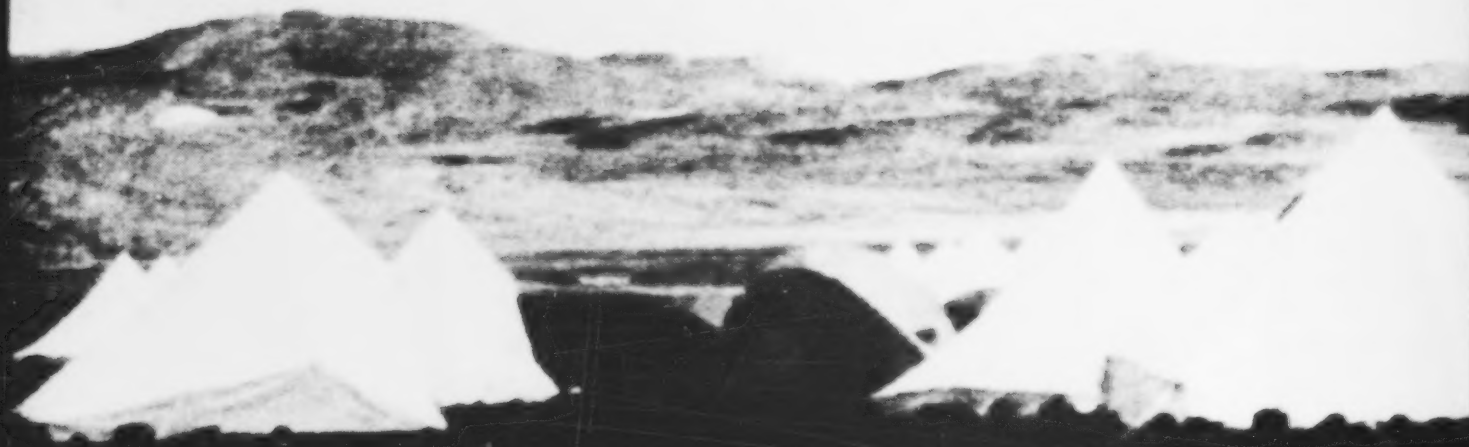
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**Structural and stratigraphic controls on
Zn-Pb-Ag mineralization at the Nanisivik
Mississippi Valley-type deposit, northern
Baffin Island, Nunavut**

Keith M. Patterson and Kelli Powis

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Abstract: The Nanisivik Mississippi Valley-type Zn-Pb-Ag deposit is located on northern Baffin Island, Nunavut. Mesoproterozoic strata in the Nanisivik area consist of a basal siliciclastic succession (Adams Sound and Arctic Bay formations), platform carbonate deposits (Society Cliffs and Victor Bay formations), and a molasse deposit (Strathcona Sound Formation). These strata are cut by east-trending normal faults interpreted as the conduits for mineralizing fluids that formed the Nanisivik massive sulphide deposits. Mineralization is localized within broad anticlines, proximal to normal faults, and is hosted by rocks of the upper and uppermost middle Society Cliffs Formation. Sulphide precipitation is interpreted to be primarily the result of reduction of ascending metalliferous fluids by previously trapped hydrocarbons. Exploration criteria for the selection of areas prospective for additional Nanisivik-style mineralization include stratigraphic, structural, and fluid-flow considerations.

Résumé : Le gîte de Nanisivik, une minéralisation de Zn-Pb-Ag de type Mississippi-Valley, est situé dans le nord de l'île de Baffin (Nunavut). Dans la région du gîte de Nanisivik, la stratigraphie du Mésoprotérozoïque consiste en une succession silicoclastique basale (formations d'Adams Sound et d'Arctic Bay), en dépôts carbonatés de plate-forme (formations de Society Cliffs et de Victor Bay) et en un dépôt molassique (Formation de Strathcona Sound). Ces strates sont recoupées par des failles normales de direction est qui constitueraient les conduits des fluides minéralisateurs à l'origine de l'accumulation de sulfures massifs du gîte de Nanisivik. La minéralisation se trouve au sein de larges anticlinaux, à proximité de failles normales, dans des roches de la partie supérieure et de la section sommitale de la partie médiane de la Formation de Society Cliffs. La précipitation des sulfures aurait résulté principalement de la réduction des fluides métallifères ascendants par des hydrocarbures préalablement piégés. Les critères de sélection de régions pouvant receler des minéralisations de type Nanisivik doivent inclure les aspects stratigraphiques et structuraux ainsi que ceux relatifs à l'écoulement des fluides.

INTRODUCTION

The Nanisivik deposits are Mississippi Valley-type Zn-Pb-Ag massive sulphide bodies hosted by Mesoproterozoic dolostone of the Society Cliffs Formation. The Nanisivik mine is located on Borden Peninsula, northern Baffin Island, Nunavut (Fig. 1). It is one of two base-metal deposits in the Canadian Arctic, the other being Polaris (Randell and Anderson, 1997). Past production and current reserves at Nanisivik total approximately 16.6 Mt at 9.07% Zn and 0.72% Pb (Nanisivik staff, pers. comm., 2001).

The present work, undertaken during the summer of 2001, included detailed mapping in the immediate vicinity of the mine, regional mapping, and examination of accessible sulphide showings, and was undertaken to characterize the stratigraphy and develop a regional model for the mineralization. Previous work in the Nanisivik area includes studies of the deposit (Olsen, 1977, 1984, 1986; Clayton and Thorpe, 1982; McNaughton and Smith, 1986; Ghazban et al., 1990, 1991), as well as regional stratigraphic studies (Lemon and Blackadar, 1963; Geldsetzer, 1973; Jackson and Ianelli, 1981; Kah, 1997; Sherman et al., 2000). This project bridges the gap between deposit-specific and regional studies. In addition to generating new concepts, this paper integrates previous work into a coherent model explaining the genesis and distribution of massive sulphide bodies in the Nanisivik area.

REGIONAL GEOLOGY

The Nanisivik region is underlain by carbonate and terrigenous clastic strata of the Mesoproterozoic Bylot Supergroup. These rocks were deposited during rifting of the Borden Basin (Jackson and Ianelli, 1981). Dolostone of the

Society Cliffs Formation hosts massive Zn-Pb-Ag mineralization at the Nanisivik deposit and several satellite massive-sulphide bodies. Archean-Paleoproterozoic high-grade gneiss and igneous rock underlie the Borden Basin (Jackson and Ianelli, 1981). No exposures of basement rock are known in the Nanisivik area, but glacially transported gneiss boulders are recognized locally. Thick siliciclastic strata of the Cambrian-Ordovician Admiralty Group unconformably overlie the Mesoproterozoic succession.

Northwest-trending normal and wrench faults affect both Mesoproterozoic and Paleozoic strata in the Nanisivik area. These faults have created the horst-and-graben topography present today. Mesoproterozoic strata have been gently folded on north-trending fold axes. The Milne Inlet Trough extends northwest from Milne Inlet to Nanisivik (Fig. 1), providing abundant exposures of Society Cliffs Formation dolostone (Jackson and Ianelli, 1981). Gabbroic dykes of the 723 ± 4/-2 Ma Franklin igneous event (Heaman et al., 1992) crosscut Mesoproterozoic rocks and generally trend northwest.

STRATIGRAPHY

In the Nanisivik area, two terrigenous formations (Adams Sound and Arctic Bay formations; Fig. 2) are overlain by two carbonate formations (Society Cliffs and Victor Bay formations; Fig. 2) and a mixed carbonate and terrigenous clastic formation (Stratheona Sound Formation). Collectively, these strata form the Bylot Supergroup. Cambro-Ordovician quartz arenite of the Gallery Formation unconformably overlies the Proterozoic strata. Mesoproterozoic map-unit abbreviations are preceded by 'N' (Neohelikian), to conform with established usage in the area.

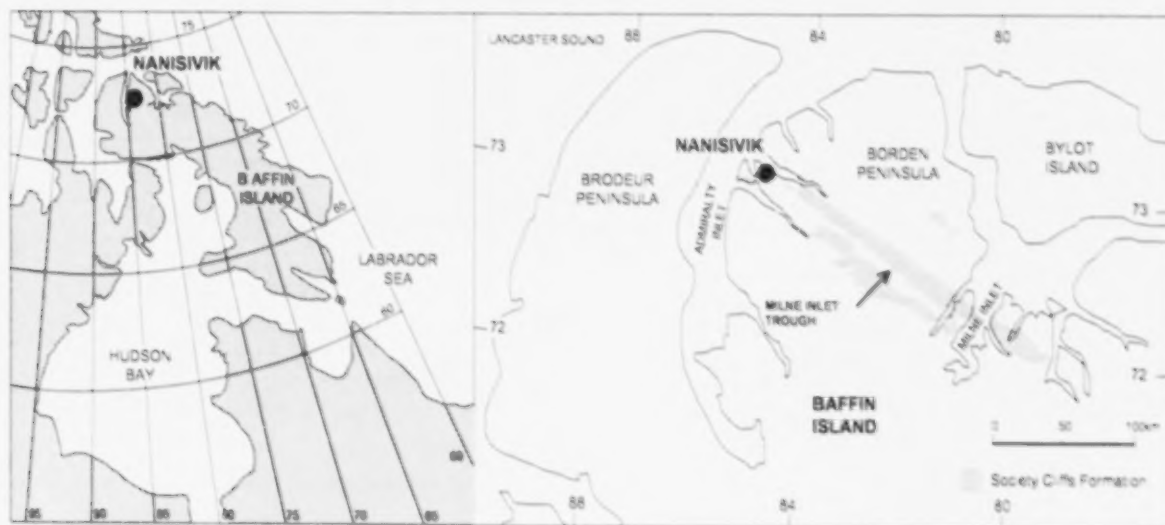


Figure 1. Location and distribution of the Society Cliffs Formation in the Nanisivik region, after Jackson and Ianelli (1981).

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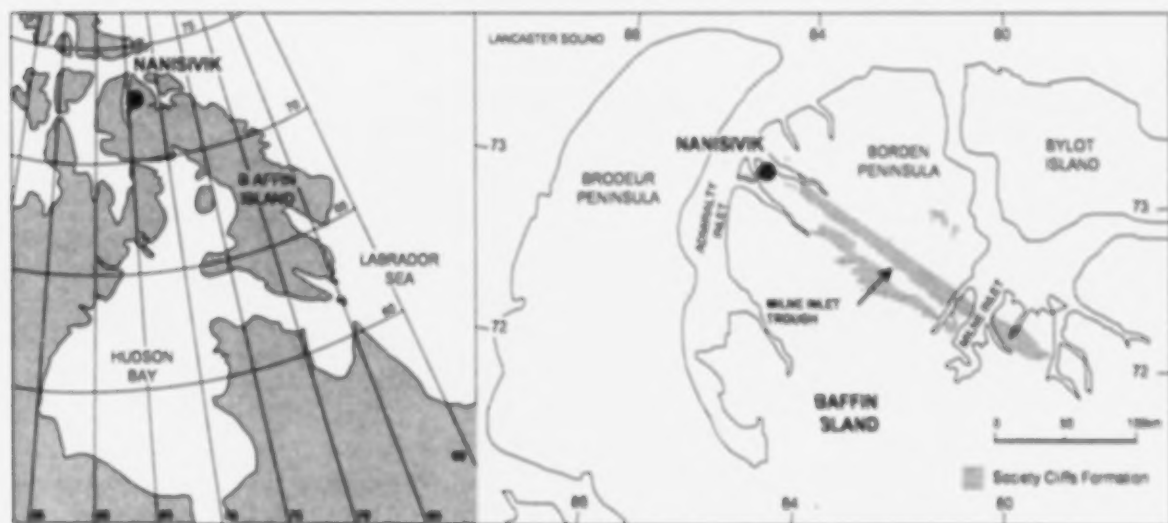


Figure 1. Location and distribution of the Society Cliffs Formation in the Nanisivik region, after Jackson and Ianelli (1981).

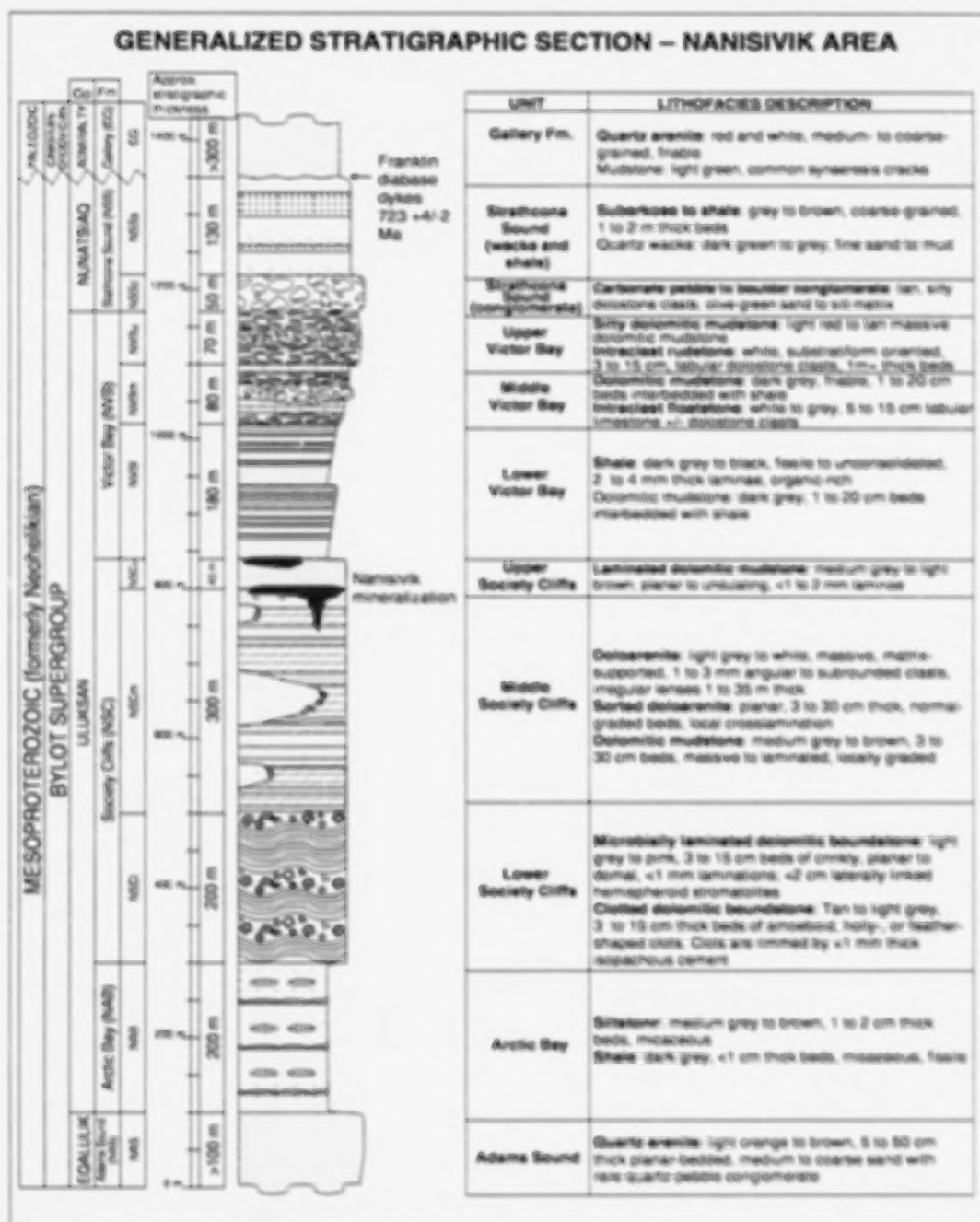


Figure 2. Generalized stratigraphic section for the Nanisivik area. Franklin intrusion age from Heaman et al. (1992); formation, group, and supergroup nomenclature from Jackson and Gunnell (1981). N = Neohelikian (obsolete equivalent of Mesoproterozoic).

Adams Sound Formation (unit NAS)

The Adams Sound Formation is exposed south of the South Boundary Fault (Fig. 3) and has been shown regionally to be in stratigraphic contact with the overlying Arctic Bay Formation (Jackson and Ianelli, 1981). It is over 100 m thick in the Nanisivik area. The contact with underlying basement is not exposed. It is a distinctive, beige- to light orange-brown-weathering, well cemented, medium- to coarse-grained quartz arenite. Quartz grains are generally well sorted and subrounded, although rare beds of quartz-pebble conglomerate (<1 m thick) are present. Heavy-mineral accumulations locally define foresets of trough and planar-tabular crossbeds. Bedding surfaces locally exhibit linguoid-crested current ripples.

Arctic Bay Formation (unit NAB)

The Arctic Bay Formation outcrops southeast and southwest of Nanisivik (Fig. 3) and is approximately 200 m thick. The contact with the overlying Society Cliffs Formation is sharp and conformable. Strata consist of medium grey to brown, micaceous, fine sandy siltstone interbedded with dark grey, micaceous, silty shale. Mica content gives bedding surfaces a distinctive sheen and commonly imparts a weak rusty weathering. Rarely, siltstone beds contain minor carbonate. Thin, wavy to lenticular-bedded siltstone is commonly ripple cross-stratified and interbedded on a 5 to 15 cm scale with shale.

Society Cliffs Formation (unit NSC)

Outcrops of the Society Cliffs Formation dominate areas at and east of the mine site. Three subdivisions are identified. Known sulphide deposits are hosted exclusively by the upper and uppermost middle subdivisions. Dolomite of the Society Cliffs Formation commonly has a strong petroleum odour, particularly within antiforms. Pyrobitumen occurs locally and may be spatially associated with mineralization.

Microbial dolomite (unit NSCI)

The lower Society Cliffs Formation is exposed at Saint George's Society Cliffs, west of Arctic Bay (~30 km southwest of Nanisivik), and is unusually well preserved at Red Rock Valley, southeast of Nanisivik (Fig. 3). The contact with the underlying Arctic Bay Formation is not well exposed. In both locations it forms steep cliffs consisting of up to 200 m of interbedded microbially laminated dolomite and clotted dolomite.

Microbially laminated dolomite shows very fine, crinkly, pink and light grey lamination that commonly grades vertically to laterally linked hemispheroid stromatolites (Fig. 4a), with local white-weathering laminoid fenestrae. Beds (1 to >50 m thick) are laterally consistent and have irregular surfaces. Discontinuous pressure-solution seams and low-amplitude stylolites commonly accentuate laminations and bedding surfaces. Rare large-scale (>100 m) bioherms

have been tentatively identified in the Red Rock Valley area; sloping bioherm margins might have contributed to the formation of unit NSCm clastic lithofacies.

Thromboids in tan-weathering dolomite (Fig. 4a) are typically holly shaped (<1 cm), wispy laminoid (2–4 cm), or amoeboid (1–5 cm), and are rimmed by <0.5 mm thick isopachous cements. Beds (3 to >100 cm thick) commonly have sharp, irregular surfaces. Rusty-weathering dolomite, hematite-stained silica, or euhedral pyrite locally replace and accentuate isopachous cements.

Intraclastic dolomite (unit NSCm)

The middle Society Cliffs Formation is predominantly intraclastic dolomite that includes several lateral facies equivalents and varies from tens to hundreds of metres in thickness. It is in gradational contact with underlying microbial dolomite of the lower Society Cliffs Formation.

The principal lithofacies of this unit is a massive, white-weathering dolomite with <1 to 3 mm, white, angular to subrounded dolomudstone intraclasts supported in a light grey dolomitic matrix. Rare dolomudstone blocks have cross-sections up to 20 cm². Massive, irregularly bedded dolomite varies in thickness from 0.7 to 35 m. These rocks are interpreted as debris on the basis of their massive texture, lateral discontinuity, and loading of underlying units.

The dolomite lithofacies is interfingering with, and grades laterally into, a package (<300 m thick) of interbedded, sorted dolomite, dolomudstone, and laminated dolomudstone to fine dolomite. Sorted dolomite forms 1 to 30 cm thick graded and ripple-cross-laminated beds, interpreted as turbidite. Thicker packages (<10 m) of laminated dolomudstone to fine dolomite are indistinguishable from portions of unit NSCu; they are differentiated primarily by their facies association and by the presence of ductile load-related deformation and lack of large tree-reef structures.

The dolomite unit is an important stratigraphic interval, because all known massive-sulphide mineralization is found within and/or above it (Fig. 5a). It has a distinctive intraclastic composition and white weathering colour, but its discontinuous nature makes small-scale stratigraphic correlation difficult.

Laminated dolomudstone (unit NSCu)

This unit is present at the top of the Society Cliffs Formation throughout the Nanisivik area. Its thickness varies from approximately 30 m to over 50 m and its lower contact with unit NSCm is sharp to gradational. Crackles, jigsaw, and mosaic breccia are common, concentrated adjacent to faults and at the upper contact with Victor Bay Formation shale. Evidence for paleokarst is generally absent (see discussion and reply, Olsen (1986) and Ford (1986)), but isopachous cements (<0.5 cm) rimming breccia clasts were identified in the Deb area (Fig. 3). This suggests that minor karst solution and brecciation might be present near the contact with the Victor Bay Formation.

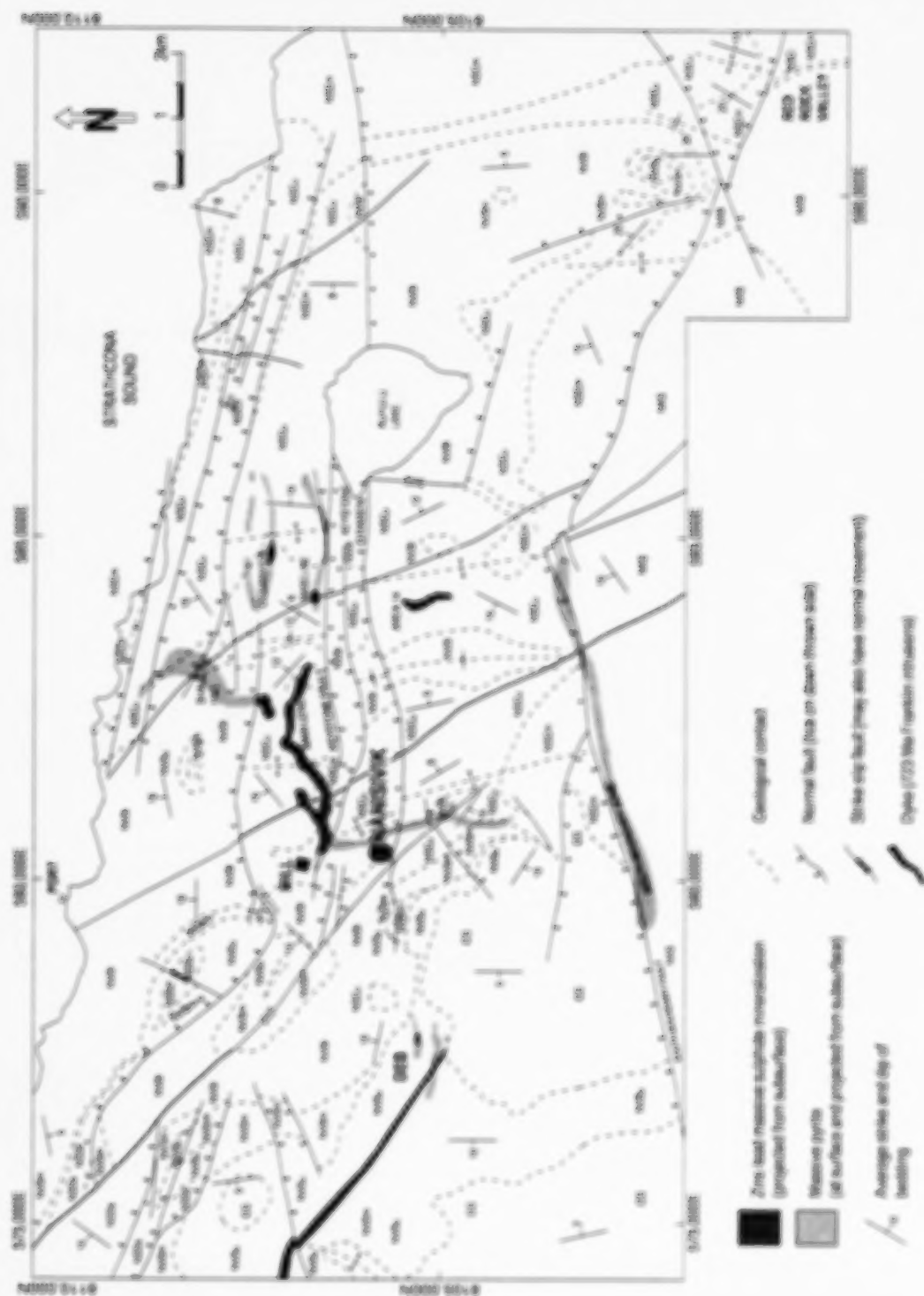


Figure 3. Simplified geology of the Namavik area showing the distribution of zirc types, structures, and named features. Lithologic abbreviations are defined in Figure 2. Note the associations of sulphide bodies with anticlines and east trending normal faults.

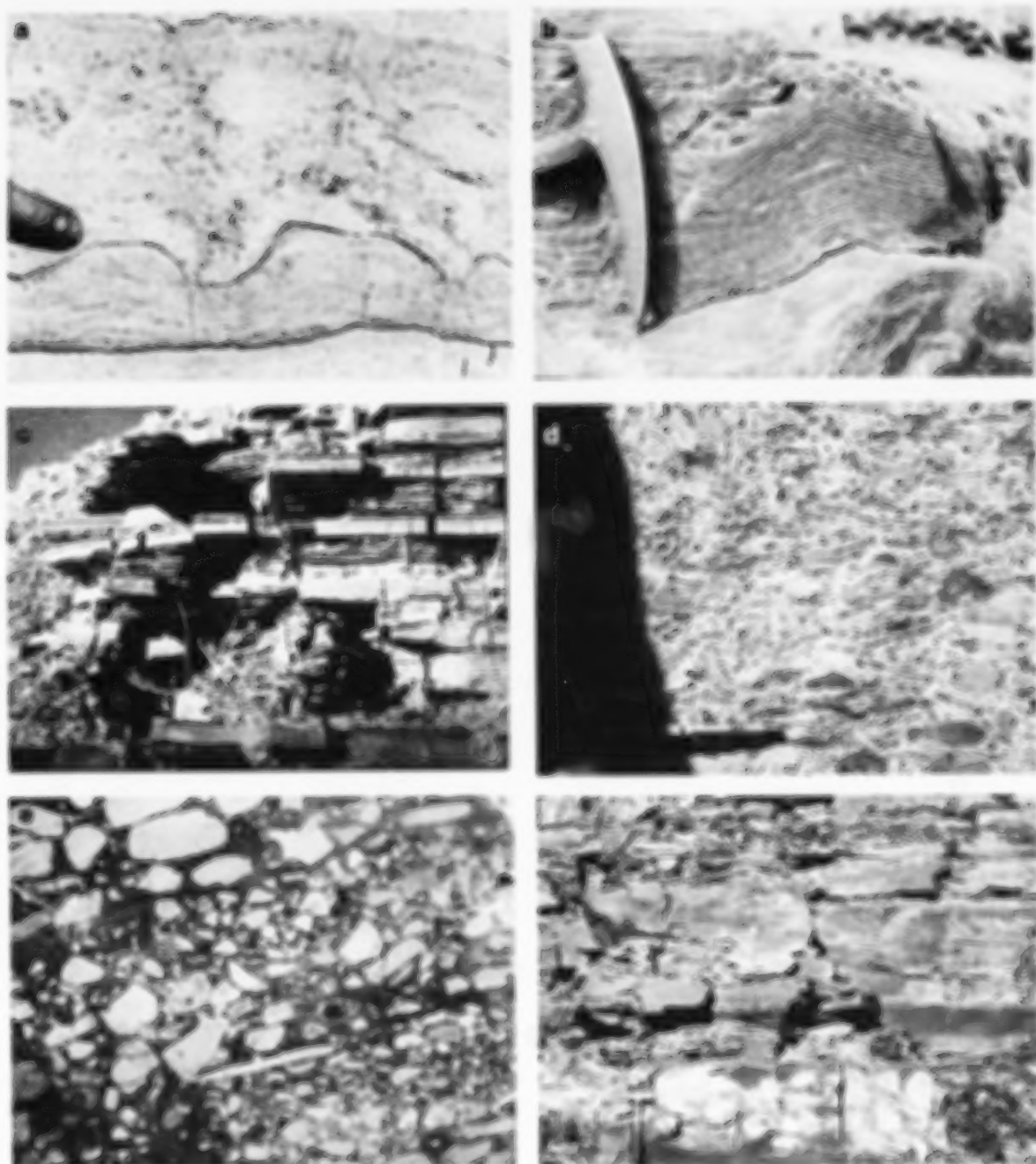


Figure 4. Nainivik area rock types. **a)** Lower Society Cliffs Formation microlithically laminated and thrombolitic dolostone. **b)** Tapered structure in upper Society Cliffs Formation laminated dolomudstone. **c)** Lower Victor Bay Formation interbedded shale and dolomudstone. **d)** Upper Victor Bay Formation dolomitic intraclastic rudstone. **e)** Smithson Sound Formation carbonate pebbles to boulder conglomerate. **f)** Smithson Sound Formation quartz wacke at contact with underlying carbonate pebbles to boulder conglomerate.

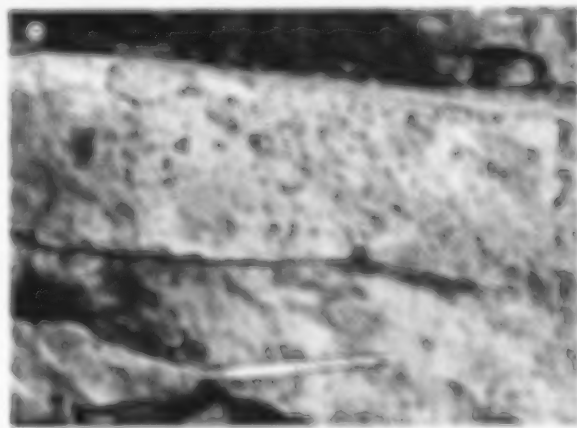
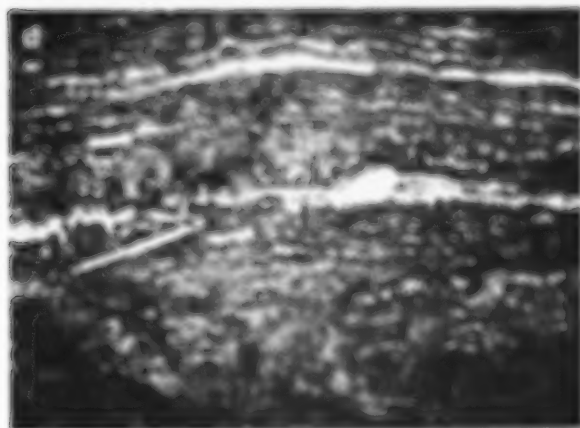
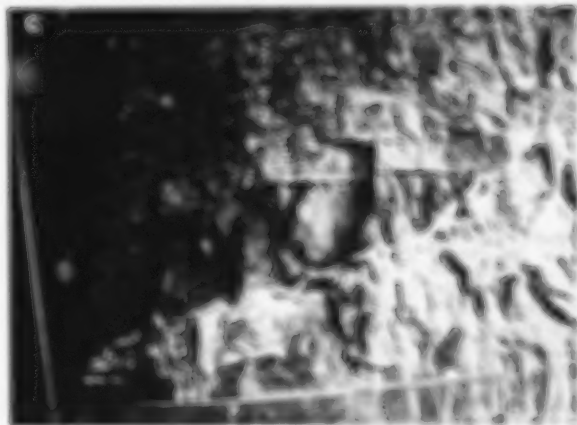
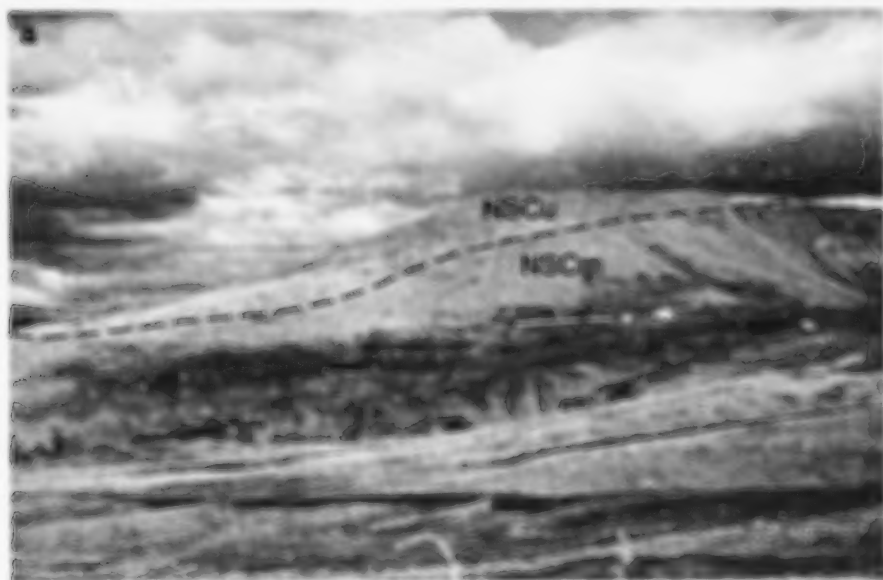


Figure 5. a) View of the main portal and mine hill. Note middle-upper Socio, Cliffs Formation contact. b) Scarre and graben morphologies in the Oromisium area, northwest of the Nanisivik mine. c) Fin of dolomite extending into, and surrounded by, massive sulphides at the B4 portal. d) Typical banded Mn-Lens sphaerulite-gyrite-quartz dolomite mineralization. e) Brecciated dolostone along the Keystone Fault.

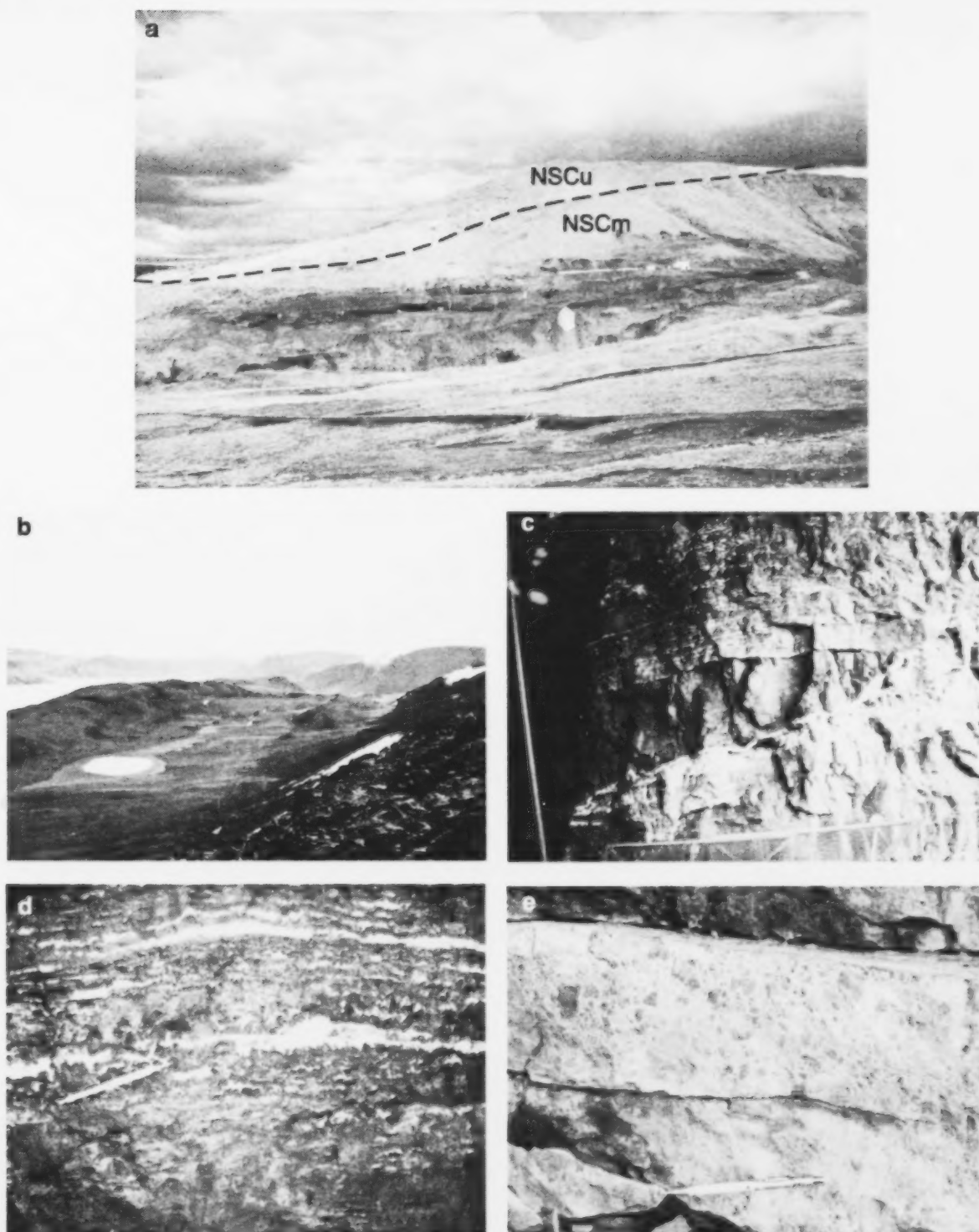


Figure 5. **a)** View of the main portal and mine hill. Note middle–upper Society Cliffs Formation contact. **b)** Horst-and-graben morphology in the Oceanview area, northeast of the Nanisivik mine. **c)** Fin of dolomite extending into, and surrounded by, massive sulphides at the 39 portal. **d)** Typical banded Main Lens sphalerite-pyrite-galena-dolomite mineralization. **e)** Brecciated dolostone along the Keystone Fault.

Laminated dolomudstone includes several lamination types, the most common being a medium brown-grey, smooth, planar-laminated (<1–2 mm) dolomudstone to fine dolarenite (Fig. 4b). Centimetre-scale, light-dark banding is defined by a variation in thickness of the light and dark laminations. Laminations are laterally continuous and are commonly deformed by teepee structures and syndimentary kink folds. Healing of larger teepees (10 cm high) is observed within the immediately overlying 0.5 m. Teepee width varies with bed thickness from less than 1 cm to over 100 cm and creates steeply to broadly undulating bedding surfaces. A "pinstriped" lamination type is also common and is due to finely crystalline, white-weathering dolomite between darker laminations.

A very fine, crinkly lamination, possibly microbial, occurs rarely in the upper Society Cliffs Formation. Thin (subcentimetric) intervals of these laminations are interbedded with thicker (1 to 2 cm) dolomudstone layers forming undulose, broadly domal, yet laterally inconsistent forms.

Victor Bay Formation (unit NVB)

The Victor Bay Formation is characterized by a gradual upward change from organic-rich pyritic shale, to dolomudstone and lime mudstone, to more intraclastic and dolomitic facies. It is exposed throughout the Nanisivik area and has been subdivided into three units.

Shale and dolomudstone (unit NVBI)

The lower Victor Bay Formation consists of interbedded black, organic-rich, fissile shale ($\pm$ pyrite) and light-grey-weathering, planar-bedded dolomudstone (Fig. 4c). Packages vary from approximately 2 to 10 m thick and are repeated a minimum of three times; total thickness of the unit is approximately 180 m. The contact with the underlying Society Cliffs Formation is sharp. The proportion of dolomudstone generally increases upsection as individual bed thicknesses increase from less than 1 cm near the base to 5 to 10 cm in the upper part of the unit. Sedimentary structures include fine parallel lamination or, less commonly, crosslamination. Nodular-bedded dolomudstone, pyrite nodules, and calcite nodules occur locally. Rarely, syndimentary faults and recumbent slump folds are present in bedded dolomudstone.

Beds (1–3 cm thick) of bladed calcite crystals oriented perpendicular to bedding-plane surfaces form a unit approximately 1 m thick in the lower Victor Bay Formation. This unit, although recessively weathering, is traceable over the entire area surrounding Nanisivik, and provides a marker horizon.

Intraclast rudstone and floatstone (unit NVBm)

The transition to the middle Victor Bay Formation is marked by the appearance of intraclast rudstone and floatstone. Rarely, limestone intraclast rudstone and floatstone can be traced into laterally equivalent, dolomitized beds. Light grey parted dolomudstone and rare black shale similar to those in

unit NVBI are interbedded with unit NVBm intraclastic layers. The presence of shale and fissile parted dolomudstone unambiguously differentiates unit NVBm from the overlying unit NVBu. The middle Victor Bay Formation is approximately 80 m thick in the Nanisivik area.

The brownish-grey intraclast floatstone facies forms lenticular to irregularly bedded bodies (<10 m thick) containing subrounded to angular, randomly oriented, blocky and tabular limestone and/or dolomudstone clasts 5 to 50 cm across. Clasts are supported in a finer grained (0.1–1 cm) floatstone matrix. These beds, interpreted as debrite, are laterally discontinuous and load underlying layers.

Brownish-grey intraclast rudstone is composed predominantly of large (5–20 cm), generally tabular, bedding-parallel, crossbedded, or randomly oriented clasts. Planar beds are less than 1 m to several metres thick.

A 3 to 15 cm thick, black-, tan-, or rust-weathering chert layer occurs within the middle Victor Bay Formation throughout the Nanisivik area and provides a small, but distinctive, marker bed.

Dolomitic intraclast rudstone (unit NVBu)

The upper Victor Bay Formation (ca. 70 m) forms a transitional unit into the terrigenous Strathcona Sound Formation. It is characterized by an absence of shale, the prevalence of dolomitic intraclastic carbonate, and the presence of terrigenous material within clastic carbonate rocks.

The dominant rock type is a pervasively dolomitized, light-grey- to brown-weathering intraclast rudstone composed of tabular, cracked clasts 3 to 15 cm across oriented subparallel to bedding (Fig. 4d). Beds are generally planar and over 1 m thick. Intraclast cracks are sharp, penetrate bedding thickness, are infilled by dolomudstone, and are commonly polygonal in bedding-plane section. Two dolomite types are present in unit NVBu intraclast rudstone, a stylolitic, light-grey-weathering dolomite and a tan-weathering, commonly vuggy, coarsely crystalline dolomite. Moving upsection, once dolostone is encountered, it persists to the contact with the Strathcona Sound Formation.

Less commonly, pervasively dolomitized debrite, similar to unit NVBm debrite lithofacies, is interbedded with and deforms other unit NVBu strata. Light grey, planar-laminated, and mudcracked dolomudstone, dolomitic intraclast grainstone/rudstone (with subcentimetric dolomudstone intraclasts and rare quartz clasts), and light-orange-weathering, silty dolomudstone characterize the upper portions of unit NVBu.

Strathcona Sound Formation (unit NSS)

The Strathcona Sound Formation is exposed west of Nanisivik (Fig. 3) and around Victor Bay. It contains several interfingering rock types of variable lateral extent that are in gradational or erosive contact with carbonate rocks of the underlying Victor Bay Formation. The boundary between the

lower Strathcona Sound Formation and the Victor Bay Formation is placed where terrigenous rocks predominate over carbonate rocks. The Strathcona Sound Formation contains two mappable units, a carbonate pebble to boulder conglomerate and a quartz wacke to subarkose that is interbedded with shale.

Carbonate pebble to boulder conglomerate (unit NSSc)

A distinctive, matrix-supported, carbonate pebble to boulder conglomerate consists of light brown to orange, subrounded to angular, 1 to 50 cm diameter silty dolomudstone clasts in a grey-green, poorly sorted quartz wacke matrix (Fig. 4e). Its thickness ranges from several metres to approximately 50 m. The matrix also contains smaller carbonate fragments and, locally, carbonate mud. Normal grading from cobble to boulder conglomerate, through pebble conglomerate, to planar-laminated quartz wacke occurs on a scale of approximately 5 m. Rare 1 m² dolostone blocks are present. Bedding thickness is proportional to grain size. Thick (0.5–1 cm) planar lamination defined by sorted carbonate and quartz silt is common at the tops of graded beds. Load casts and flame structures are common where conglomerate overlies quartz wacke beds (3–15 cm). Imbrication of larger tabular clasts is evident locally.

The Strathcona Sound Formation boulder conglomerate is generally confined to paleolows and/or near interpreted paleofault scarps. On the basis of this spatial distribution and lithology, this facies is interpreted to have been deposited contemporaneously with rifting.

Locally, a red, carbonate-cemented, laterally discontinuous siltstone underlies the carbonate pebble to boulder conglomerate. It conformably overlies the Victor Bay Formation and locally cuts down into it. The siltstone is rippled, contains soft-sediment deformation structures, and is interbedded with thin beds of dolomitic intraclast grainstone/rudstone containing quartz clasts. This unit is considered to be transitional between Victor Bay and Strathcona Sound formations.

Interbedded quartz wacke and shale (unit NSSs)

The transition from boulder conglomerate to quartz wacke and shale (NSSs) is gradational. Beds of carbonate pebble to boulder conglomerate within the quartz wacke and shale unit are common within 10 m of the contact (Fig. 4f). Quartz wacke and shale are interbedded at scales ranging from 1 to 200 cm. This unit is green- to dark-grey- weathering, planar bedded, and forms a thick (>130 m), monotonous succession. The tops of thicker quartz wacke beds commonly contain ripple crosslamination that is easily recognized by its white- and green-weathering grains.

Gallery Formation

Phanerozoic rocks of the Cambro-Ordovician Gallery Formation unconformably overlie Mesoproterozoic strata and are exposed predominantly west of Nanisivik (Fig. 3).

The Gallery Formation forms a thick (>300 m) succession of interbedded red and white, poorly cemented, medium- to fine-grained quartz arenite with trough and planar-tabular crossbedding. Quartz grains are generally well sorted and subangular to subrounded. Beds are less than 0.02 m to 1 m thick. The Gallery Formation is easily identifiable by its deep red hematite-stained colour and friable texture, and commonly forms distinctive red and buff cliffs throughout the Borden Peninsula.

STRUCTURE

The region surrounding the Nanisivik deposit is characterized by flat-lying to gently dipping strata that are cut by east-striking, steeply dipping normal faults (Fig. 3). North-south extension resulted in normal faulting and the associated horst-and-graben geomorphology of the Nanisivik area (Fig. 5b). Regionally, this extension is attributed to the North Baffin Rift Zone; in the Nanisivik area, the Milne Inlet Trough is the controlling structure (Jackson and Ianelli, 1981). On the south shore of Strathcona Sound, fault blocks have generally been down-dropped to the north, indicating that the centre of the Milne Inlet Trough likely lies under Strathcona Sound, north of Nanisivik (Fig. 3). The South Boundary Fault, 1 km south of the Nanisivik mine, has approximately 600 to 1000 m of north-side-down displacement and is interpreted to be the controlling structure in the immediate Nanisivik area. The many second-order normal faults throughout the Nanisivik area generally show 50 to 100 m of normal movement. In addition to the east-trending normal faults, rare strike-slip transfer structures are also mapped (Fig. 3).

Extensional tectonism has been extraordinarily long-lived in the Borden Basin. Clastic lithofacies of likely syntectonic origin are present in the Society Cliffs and Strathcona Sound formations and suggest that rifting had been initiated by the Mesoproterozoic (Jackson and Ianelli, 1981; this study). Rarely, normal faults cut rocks of the Cambro-Ordovician Gallery Formation and demonstrate continued extension during Paleozoic time. Modern fault scarps and normal faults that cut glacial deposits indicate that extension has continued to the present (Jackson and Ianelli, 1981).

In the Nanisivik area, strata have been gently warped into large-scale, open folds with north-trending axial traces (Fig. 3). These folds have amplitudes of 100 to 200 m, wavelengths of 1 to 2 km, and are of critical importance in controlling the distribution of mineralization. They are interpreted to have formed synchronously with ongoing rifting owing to weak dextral wrenching in a transtensional regime. The exact timing and duration of folding is uncertain, but it took place prior to massive-sulphide precipitation.

Northwest-trending gabbroic dykes of the Franklin intrusive event (723 ±4/-2 Ma; Heaman et al., 1992) crosscut Mesoproterozoic strata (Fig. 3). These dykes both crosscut and are cut by normal faults, showing that extension both pre-dates and post-dates the Franklin event.

CONTROLS ON MINERALIZATION

The model proposed here to explain the localization of massive sulphide deposition in the Nainivik area invokes structurally controlled fluid conduits and structurally created fluid traps within permeable dolostone units. The identification of potential conduits, traps, and prospective stratigraphy provides a means of predicting the potential locations of undiscovered massive sulphide bodies.

Sulphide bodies at Nainivik are dominantly massive pyrite, which replaces dolostone along high angle normal faults and forms mantos that shallowly crosscut bedding (Fig. 6). Sphalerite and galena are less extensive, leaving many barren pyrite bodies. Approximately 100 Mt of iron sulphide are present at Nainivik (Nainivik staff, pers. comm., 2001), in comparison to the 16.6 Mt of base metal production plus reserves.

Numerous previous studies have addressed the physico-chemical environment and timing of massive sulphide deposition at the Nainivik deposit (Ford, 1981; Clayton and

Thorpe, 1982; Curtis, 1983; Olsen, 1983; McNaughton and Smith, 1986; Arne, 1986; Ghazban et al., 1990, 1991). Controversy exists over the physical environment into which sulphides were precipitated (Ford, 1986; Olsen, 1986), specifically whether an open cave system was present prior to sulphide deposition. Previous models include a large, open, integrated cave system that was later filled by sulphides (Olsen, 1977, 1984); a developing cave system that was filled synchronously with sulphides (Clayton and Thorpe, 1982; Ford, 1986); minor karst control with permeability-controlled location of dolostone replacing sulphides (Curtis, 1983; Ford, 1986); and fluid mixing models that do not necessarily require any karst-enhanced porosity (McNaughton and Smith, 1986). It is beyond the scope of this paper to delve into the details of deposit genesis, but some discussion is needed, as it bears directly on regional exploration criteria.

With the exception of limited paleokarst features exposed in the Deb area (Fig. 3), this study has found no evidence for significant karst control on mineralization. Underground exposures yield ample evidence for replacement of dolostone as the main mechanism for pre-deposition. This includes

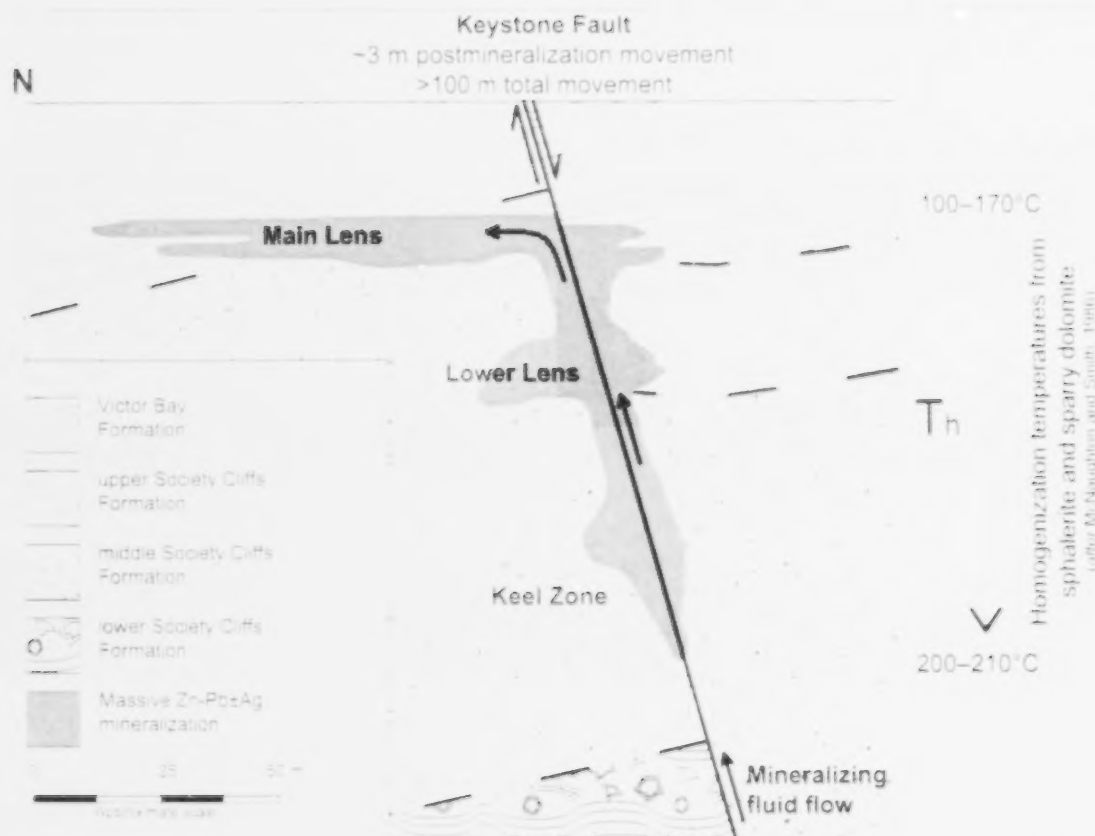


Figure 6. Schematic cross-section through the Nainivik Main Lens and Keel Zone. Note the association of Keystone Fault and Keel Zone mineralization. Homogenization temperatures are from fluid inclusions trapped within sphalerite and sparry dolomite (data from McNaughton and Smith, 1986).

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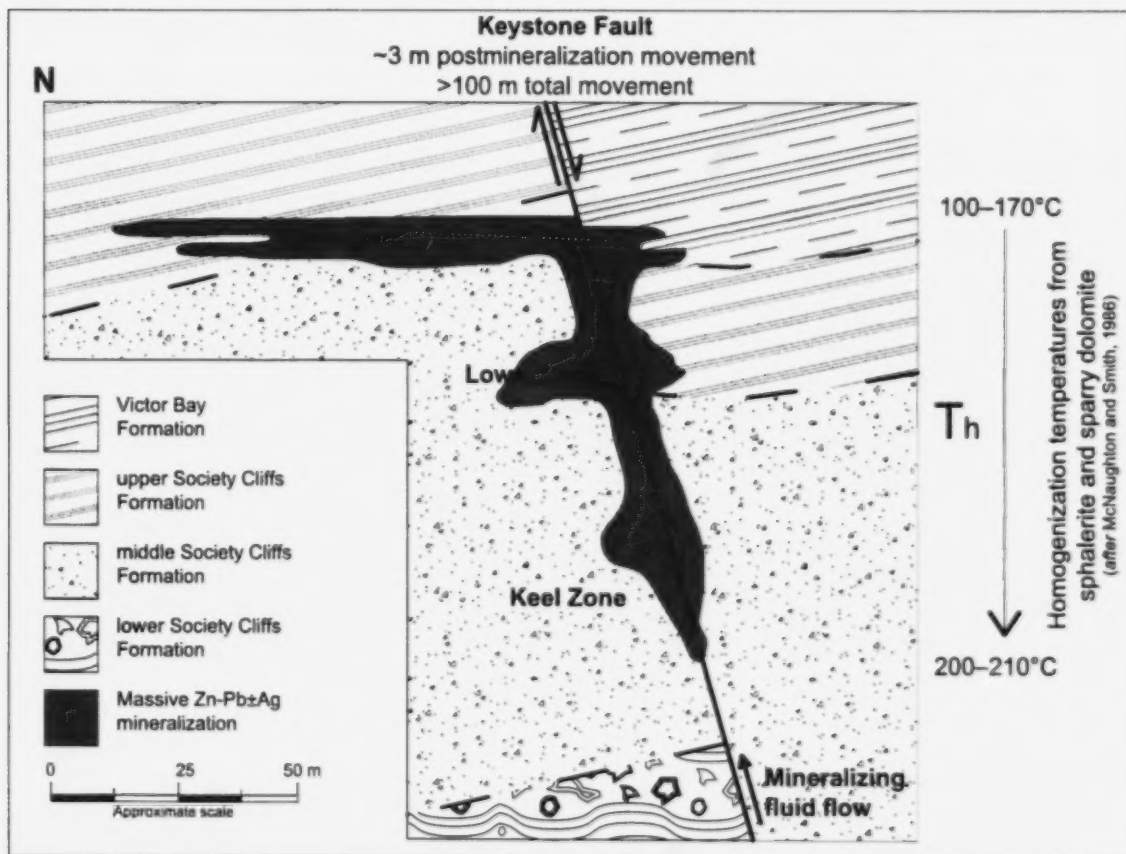


Figure 6. Schematic cross-section through the Nanisivik Main Lens and Keel Zone. Note the association of Keystone Fault and Keel Zone mineralization. Homogenization temperatures are from fluid inclusions trapped within sphalerite and sparry dolomite (data from McNaughton and Smith, 1986).

dolostone blocks that are completely surrounded by sulphides, yet have not been rotated and have not moved relative to wallrock. Also, large (20 to 30 m), unsupported fins of dolostone (Fig. 5c) protrude into massive sulphides; given their 1 to 3 m thickness, it is difficult to envision their formation in an open cave system. These features do not preclude the possibility of minor karstification or primary sedimentary fragmentation, which might have had local control on permeability and hence on the location of mineralization.

Sulphides are localized along east-trending normal faults, with mantos extending off the faults into favourable strata (Fig. 6). Vertical temperature gradients existed along these faults; fluids that precipitated sulphides in the deeper Keel Zone were 30°C to 50°C warmer than fluids responsible for the main sulphide body (Fig. 6; McNaughton and Smith, 1986). Additional regional evidence for fluid flow along east-trending normal faults is provided by solution breccias (rarely with a fine-grained pyrite matrix) commonly found along these structures (Fig. 5e).

Broad anticlines bounded by normal faults host most of the known sulphide bodies in the Nanisivik area (Fig. 3). It is suggested that these anticlines acted as fluid traps and contained hydrocarbon reservoirs. Evidence for the former presence of hydrocarbons includes the strong petroleum odour associated with dolostone of the Society Cliffs Formation and rare pyrobitumen.

Given the structural framework outlined above for the location of sulphides, a hydrothermal system is envisioned in which oxidized metalliferous brines migrated along normal faults. Where these faults crosscut antiforms, hydrothermal fluids were reduced by gaseous hydrocarbons trapped within the antiforms (see Anderson, 1991). Sulphates, either locally derived or transported by the fluid, were thermochemically reduced by the gas, providing a ready source of H₂S to form the sulphide bodies. In addition to explaining the structural features noted above, this model provides a simple explanation for the anomalously horizontal upper surface of the Nanisivik Main Lens (varies <3 m vertically over ~3 km strike length).

EXPLORATION CRITERIA

Significant potential for the discovery of additional Nanisivik-style Zn-Pb-Ag deposits exists within dolostone of the Society Cliffs Formation along the Milne Inlet Trough. The Society Cliffs Formation is exposed over approximately 180 km between Nanisivik and Milne Inlet (Fig. 1); this region is underexplored and may provide an attractive exploration target.

Criteria for the selection of specific exploration targets within the Milne Inlet Trough are as follows, in order of importance.

1. All known Nanisivik-style mineralization occurs within the upper part of the middle Society Cliffs Formation and/or the upper Society Cliffs Formation. Rarely, mineralization extends upsection to the contact with the

lower Victor Bay Formation. Location within the middle to upper Society Cliffs Formation is considered essential to the Nanisivik mineralization model.

2. East-trending normal faults are associated with all known mineralization in the Nanisivik area and are interpreted to be the conduits for metalliferous fluids. The presence of first- or second-order, east-trending normal faults is also considered essential to the Nanisivik mineralization model.
3. Most massive-sulphide bodies in the Nanisivik area are located within broad anticlines. These anticlines are interpreted to have contained trapped hydrocarbons; sulphide deposition resulted from the reduction of ascending metalliferous fluids by gaseous hydrocarbons. The identification of these broad structures is not trivial, because interlimb angles are generally between 160° and 170°, and outcrop-scale variations in bedding can mask their presence.
4. Solution breccias are present along and peripheral to east-trending normal faults in the immediate vicinity of mineralization at Nanisivik. The presence of these breccias is considered prospective assuming suitable sulphide deposition sites exist.
5. Pyrite (possibly with sphalerite and galena) is rarely present as matrix within solution breccias and along fractures proximal to mineralization. This is not considered an essential feature of the Nanisivik model because sulphides are only rarely seen above and peripheral to the Main Lens at Nanisivik. The presence of small sulphide zones is considered positive, however, for the general prospectivity of an area.

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REFERENCES

- Anderson, G.M.
1991: Organic maturation and ore precipitation in Southeast Missouri; *Economic Geology*, v. 86, p. 909-926.
- Arne, D.C.
1986: A study of zonation at the Nanisivik Zn-Pb-Ag mine, Baffin Island, Canada; M.Sc. thesis, Lakehead University, Thunder Bay, Ontario, 194 p.

Clayton, R.H. and Thorpe, L.

1982: Geology of the Nanisivik zinc-lead deposit; Geological Association of Canada, Special Paper 25, p. 739-758.

Curtis, L.W.

1984: Geologic study of the Nanisivik area; report submitted to Strathcona Mineral Services, Toronto, 262 p.

Ford, D.C.

1981: Report upon the karstic features of the sulphide deposits at Nanisivik, Baffin Island; report submitted to Strathcona Mineral Services, Toronto.

1986: Genesis of paleokarst and strata-bound zinc-lead sulfide deposits in a Proterozoic dolostone, northern Baffin Island, Canada — a discussion; *Economic Geology*, v. 81, p. 1562-1563.

Geldsetzer, H.

1973: The tectono-sedimentary development of an algal-dominated Helikian succession on northern Baffin Island, N.W.T.; in *Symposium on Arctic Geology*, (ed.) J.D. Aitken and D.J. Glass; Geological Association of Canada, Memoir 19, p. 99-126.

Ghazban, F., Schwarcz, H.P., and Ford, D.C.

1990: Carbon and sulphur isotope evidence for in situ reduction of sulfate, Nanisivik lead-zinc deposits, Northwest Territories, Baffin Island, Canada; *Economic Geology*, v. 85, p. 360-375.

1991: Stable isotope composition of the hydrothermal fluids responsible for the Nanisivik Zn-Pb deposits, Northwest Territories, Baffin Island, Canada; *Applied Geochemistry*, v. 6, p. 257-266.

Heaman, L.M., LeCheminant, A.N., and Rainbird, R.H.

1992: Nature and timing of Franklin igneous events, Canada: implications for Late Proterozoic mantle plume and the break-up of Laurentia; *Earth and Planetary Science Letters*, v. 109, p. 117-131.

Jackson, G.D. and Iannelli, T.R.

1981: Rift-related cyclic sedimentation in the Neohelikian Borden Basin, northern Baffin Island; in *Proterozoic Basins of Canada*, (ed.) F.H.A. Campbell; Geological Survey of Canada, Paper 81-10, p. 269-302.

Kah, L.C.

1997: Sedimentological, geochemical, and paleobiological interactions on a Mesoproterozoic carbonate platform: Society Cliffs Formation, northern Baffin Island, Arctic Canada; Ph.D. thesis, Harvard University, Cambridge, Massachusetts, 292 p.

Lemon, R.R.H. and Blackadar, R.G.

1963: Admiralty Inlet area, Baffin Island, District of Franklin; Geological Survey of Canada, Memoir 328, 84 p.

McNaughton, K. and Smith, T.E.

1986: A fluid inclusion study of sphalerite and dolomite from the Nanisivik lead-zinc deposit, Baffin Island, Northwest Territories, Canada; *Economic Geology*, v. 81, p. 713-720.

Olsen, R.A.

1977: Geology and genesis of zinc-lead deposits within a late Proterozoic dolomite, northern Baffin Island, N.W.T.; Ph.D. thesis, University of British Columbia, Vancouver, British Columbia, 317 p.

1984: Genesis of paleokarst and strata-bound zinc-lead sulfide deposits in a Proterozoic dolostone, northern Baffin Island, Canada; *Economic Geology*, v. 79, p. 1056-1103.

1986: Genesis of paleokarst and strata-bound zinc-lead sulfide deposits in a Proterozoic dolostone, northern Baffin Island, Canada — a reply; *Economic Geology*, v. 81, p. 1563-1566.

Randell, R.N. and Anderson, G.M.

1996: Geology of the Polaris Zn-Pb deposit and surrounding area, Canadian arctic archipelago; *Society of Economic Geologists*, Special Publication no. 4, p. 307-319.

Sherman, A.G., James, N.P., and Narbonne, G.M.

2000: Sedimentology of a late Mesoproterozoic muddy carbonate ramp, northern Baffin Island, Arctic Canada; *Society for Sedimentary Geology*, Special Publication 67, p. 275-294.

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